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A LINEAR SOLUTION OF LIFT INTERFERENCE IN SQUARE TUNNELS WITH SLOTTED TEST SECTIONS OF FINITE LENGTH

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LIST OF SYMBOLS

C_L	lift coefficient
C_p	pressure coefficient
C	tunnel cross sectional area
h	tunnel semi-height
K	slot parameter
ℓ	length of slotted section
M_∞	free stream Mach number
p_∞	free stream pressure
p_p	plenum pressure
P	porosity parameter
s	wing span
u,v,w	velocity components
x,y,z	Cartesian coordinates
β	compressibility parameter, $(1 - M_\infty)^{\frac{1}{2}}$
Γ	vortex strength
δ	lift interference factor, $wC/2\Gamma s$
σ	source strength
Φ	perturbation velocity potential
Δx_p	length of panels

Subscript

i	wall induced
m	model induced
im	induced by image vortices
x,y,z	denotes partial differentiation
σ'	induced by wall singularities

Superscript

$'$	denotes incompressible quantities

ABSTRACT

A numerical program has been developed to determine the effects on lift interference of the finite length of the slotted portion of a square tunnel. Also analyzed by the program are the effects produced by small variations of static pressure between upper and lower plenum, and by boundary layer development on upper and lower walls downstream of the slotted section. In the flow model, based on compressible linear theory, the wing is represented by a single vortex and the wall induced perturbations are obtained by superimposing the effects of a series of images of the central vortex and of a distribution of sources and sinks on panels along the tunnel walls. The present results can be indicative of the magnitude and of the trends of the interference patterns associated with slotted test sections of finite length at high subsonic Mach numbers.

INTRODUCTION

The classical approach to the study of tunnel wall interference in subsonic flow is to consider test sections of infinite length, represent the model by appropriate singularities (vortices , doublets, etc.), and obtain closed form solutions for the interference parameters by satisfying the wall boundary conditions for the different cases of solid, porous and slotted walls. In actual wind tunnels which have ventilated test sections of finite length, the interference experienced by the model may be altered to a certain degree by the discontinuities in flow conditions at the beginning and at the end of the ventilated portion. This may be particularly true when testing lifting three-dimensional models since the large velocity components created by the trailing vortices not only produce conditions of inflow and outflow between the plenum and the test section but, subsequently, are constrained inside the solid portion of the tunnel downstream of the ventilated section. In addition, the low momentum air that enters the tunnel from the upper plenum and is accelerated by the tunnel flow may decrease the momentum of the tunnel flow and create interference pressure gradients. At the same time, the flow of tunnel air into the plenum may lose momentum when mixing with the plenum air and thus establish pressure differentials between top and bottom portions of the plenum, changing locally, although slightly, the plenum pressure with respect to the assumed free stream static value.

Of current concern is the quantitative determination of these effects for the study of three-dimensional flow fields in transonic tunnels. Present capabilities in transonic numerical analysis could allow for such a determination, e.g., Reference (1). However, in order to illustrate the important trends of the phenomena under consideration and single out the relevance of the parameters effecting the interference, simple and more readily computable flow models based on a compressible linear theory can be utilized. For this reason, linearized solutions have been considered for the flow fields of interest in the present investigation.

Considered herein is the case of a lifting configuration (where an unswept wing is represented by a single horseshoe vortex) in a square tunnel with slotted walls of finite length on all four sides. The effects on lift interference

generated by the finite length of the ventilated portion of the test section and by small differences between upper and lower plenum pressure are investigated. Also investigated are the effects produced by variations of wall boundary conditions downstream of the slots to simulate symmetric and asymmetric (with respect to tunnel centerline) boundary layer development along the upper and lower solid walls downstream of the slots.

The solution technique that has been adopted for the consideration of slotted test sections of finite length is a modification of the numerical method of Keller and Wright [2] and of Keller[3]. A double series of images of the central vortex about the four tunnel walls is first introduced, as if the walls were solid, so as to nearly satisfy the solid wall boundary conditions upstream and downstream of the slotted region. The tunnel walls are then divided into rectangular panels which are represented by source or sink distributions of unknown strength. The appropriate boundary conditions are satisfied at the centroid of each panel leading to a matrix equation whose solution yields the panel source strength. The wall panel strength distributions, together with the image vortices, are then used to calculate the wall interference at any point in the tunnel. The introduction of image vortices permits an improved satisfaction of the wall boundary conditions upstream and downstream of the slots with fewer wall panels.

This numerical method was employed since analytical solutions, e.g. References (4) and (5), are limited in general to infinite-length test sections and would not readily allow for the combination of ventilated and solid wall boundary conditions or for the more general wall boundary conditions considered herein. In the present analysis, the surface singularity distribution is taken constant in each panel, which is appropriate for the integrated slotted wall condition, as established in Reference (2). The model and analysis have the flexibility to allow for the inclusion of other wall boundary conditions and distributions of wall singularities (as in Reference 3), as well as of a more general representation of tunnel models, such as lifting wings and wing-centerbody-tail configurations, by surface distributions of elementary vortices and of other singularities.

METHOD OF SOLUTION

Following standard methods, and in the coordinate system of Figure (1), the problem is expressed in the term of the linearized compressible equation

$$\beta^2 \Phi_{xx} + \Phi_{yy} + \Phi_{zz} = 0$$

where

$$\Phi = \Phi_m + \Phi_i$$

Φ_m being the perturbation potential of the flow about the model in free air and Φ_i being the potential induced by the wall constraints. The basic configuration that is examined is the one of Figure (1), with the four tunnel walls slotted in the region of the model and solid upstream and downstream. The boundary conditions in the slotted portion extending from ℓ_1 to ℓ_2 are assumed to be of the form

$$\begin{aligned} &\Phi_x \pm K\,\Phi_{xz} = 0, \qquad z = \pm h, \qquad \ell_1 < x < \ell_2 \\ &\Phi_x \pm K\,\Phi_{xy} = 0. \qquad y = \pm h, \qquad \ell_1 < x < \ell_2 \end{aligned} \tag{1}$$

where K is the slot parameter. In the solid region they are

$$\begin{aligned} &\Phi_z = 0 \qquad z = \pm h \\ &\Phi_y = 0 \qquad y = \pm h \end{aligned} \tag{2}$$

Modifications to these boundary conditions, to account for different pressure between upper and lower plenum and different shapes of solid walls, are described later.

The model considered is an unswept finite wing which is represented by a single horseshoe vortex of strength Γ to provide the value of Φ_m at the tunnel walls. The induced potential Φ_i is provided by a proper distribution of singularities at the wall or external to it, which satisfy, together with the model induced perturbations, the boundary conditions (1) and (2).

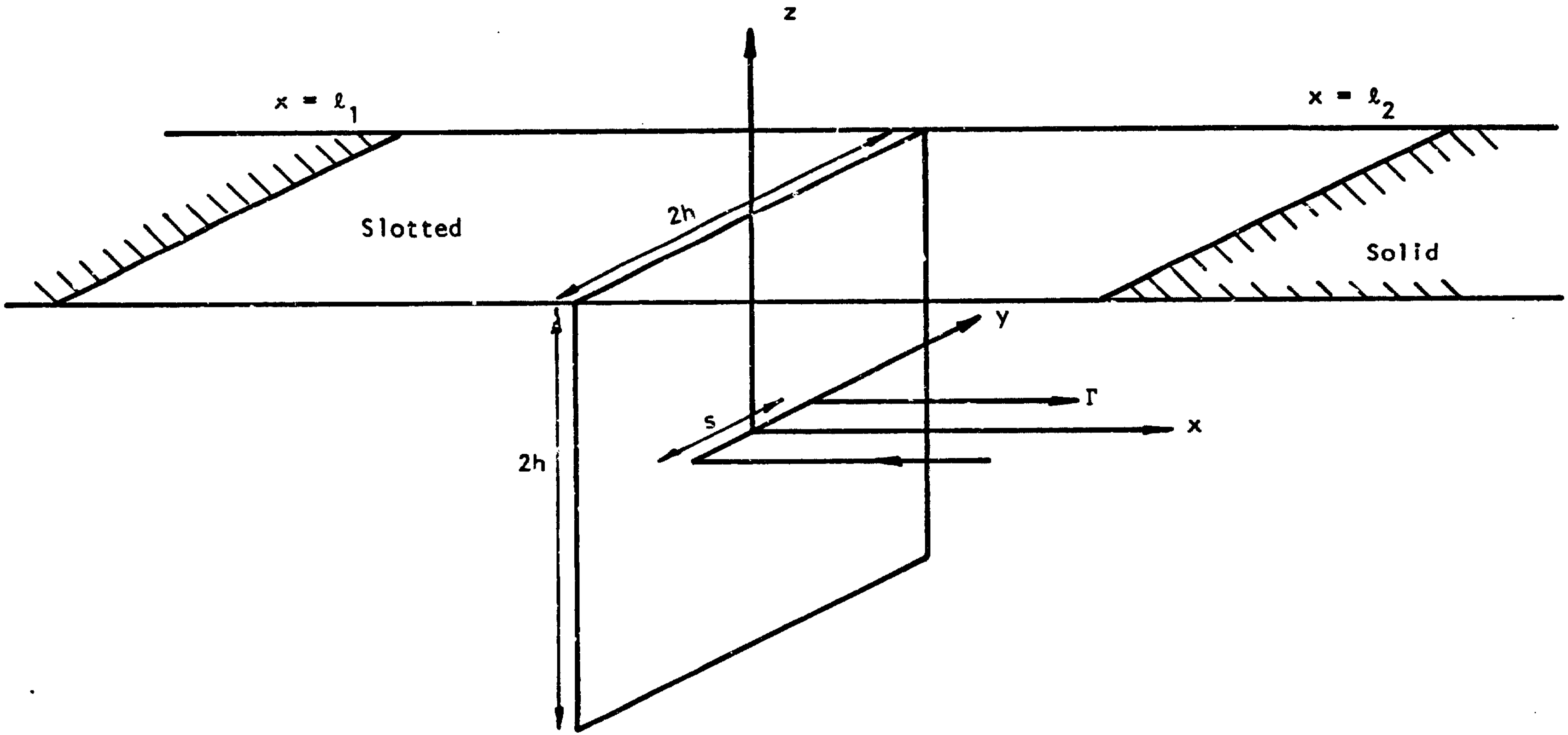

FIGURE 1. SCHEMATIC OF MODEL-TUNNEL CONFIGURATION

The solution is sought by casting the problem into an incompressible form utilizing the compressibility transformations.

$$x' = x/2\beta h \qquad y' = y/2h \qquad z' = z/2h \qquad \phi' = \beta\phi$$

and with

$$K' = K \quad \text{and} \quad \Gamma' = \beta\Gamma$$

where the prime quantities denote the incompressible values.

The velocity potential induced by the vortex of strength Γ' and span s' is taken as

$$\phi'_m = \frac{\Gamma'}{4\pi} \left\{ \tan^{-1}\left[\frac{x'(y'+s')}{z'(x'^2 + z'^2 + (y'+s')^2)^{\frac{1}{2}}} \right] - \tan^{-1}\left[\frac{-(y'+s')}{z'} \right] - \tan^{-1}\left[\frac{x'(y'-s')}{z'(x'^2 + z'^2 + (y'-s')^2)^{\frac{1}{2}}} \right] - \tan^{-1}\left[\frac{-(y'-s')}{z'} \right] \right\} \tag{3}$$

This equation is obtained by the integral $\phi' = \int_{-\infty}^{x'} u'dx'$ where u' is the velocity induced by attached and trailing vortices, as given in Reference (6).

The distribution and strength of the singularities providing the interference potential Φ_i is obtained as follows. A double series of images of the central vortex is first taken as if the walls were solid. Each image vortex has a perturbation potential Φ'_{im} of the form of Equation (3) with the proper sign and the proper distances. Then, following the procedure of References (2) and (3), the tunnel walls are divided into longitudinal strips, each of which is divided into a number of rectangular panels of arbitrary length. Each panel is represented by a source (or sink) distribution of constant but unknown strength σ'. The potential $\Phi'_{\sigma'}$ induced by each element of strength σ' is given in Reference (2). The strengths of the vortex images alternate in

sign in the z-direction and are all positive in the y-direction. Since the tunnel under consideration consists of solid walls upstream and downstream of the slotted section, use of even a finite number of vortex reflections will cause the boundary conditions on the panels in the solid region to be nearly satisfied. This results in small source strength distributions on these panels and allows for use of larger and, therefore, fewer panels in the solid region. Use of vortex reflections also results in the solid wall boundary condition being nearly satisfied up and downstream of the axial range in which panels are taken.

As discussed in Reference (2), for a constant strength distribution in each element, the integrated form of the slotted wall boundary condition is appropriate. Accordingly integration of Equation (1), yields

$$\Phi' - \Phi'_o \pm K' \left(\phi'_{z'} - \Phi'_{z',o}\right) = 0$$

$$\frac{\ell_1}{2\beta h} < x' < \frac{\ell_2}{2\beta h} \qquad (4)$$

$$\Phi' - \Phi'_o \pm K' \left(\Phi'_{y'} - \Phi'_{y',c}\right) = 0$$

where subscript o refers to quantities at the beginning of the slotted region. Note that the similarity variable describing the finite slotted lengths are $\ell_1/2\beta h$ and $\ell_2/2\beta h$. Thus, satisfaction of Equations (2) and (4) in terms of the model potential Φ'_m (known) and the potentials Φ'_{im} (known) and $\Phi'_{\sigma'}$, given by the image vortices and by the wall singularities, respectively, yields a set of linear homogeneous equations, which by matrix inversion give the unknown panel strengths σ'. From these and from the image vortices, and by application of the compressibility transformations in an inverse manner, the wall induced interference in terms of $u = u'/\beta^2$, $v = v'/\beta$ and $w = w'/\beta$ is computed at any point in the tunnel. The lift interference is customarily cast in terms of the parameter $\delta = w_i C/2\Gamma s$ where w_i is the induced velocity along the tunnel axis. This parameter is invariant under transformation. Thus, the axial distribution of δ in terms of $x' = x/2\beta h$ and of the scaled slotted test section lengths $\ell_1/2\beta h$ and $\ell_2/2\beta h$ (see Equation 4) is similar (and thus independent specifically of Mach number and tunnel height).

In carrying out the numerical computations, eight reflections of the central vortex about each wall have been used. Also, the panels are chosen such that the stations at which the wall changes from closed to slotted are located at the panel boundary. In order to expedite the numerical solution, further advantage was taken of the symmetries of the problem. For the problem of a horseshoe vortex in a slotted-solid tunnel with straight walls and equal slots on all four sides not only is there a y-symmetry but, in addition, the problem is anti-symmetric with respect to z. In fact, the source strength distributions on the bottom wall and on the lower half of the sidewall are equal to and of opposite sign from the distributions on the upper wall and the upper half of the sidewall, respectively. This is evident when Φ_m is substituted in the boundary conditions (1) and (4). Under the above conditions it is only necessary to compute the wall source strength distributions at panels along one quarter of the tunnel cross section (i.e. one-half along the top and one-half along the sidewall). Thus, the number of equations to solve is reduced by a factor of four, although the influence of all the panels around the tunnel must be included in the boundary conditions at the centroids of the panels chosen. For the case where the lower wall plenum pressure is perturbed or the downstream upper solid wall is curved, only the y-symmetry remains; still, the wall sources can be computed in the half plane, that is along one-half of the tunnel cross section.

NUMERICAL RESULTS

The typical configuration considered here is a lifting wing of unit span and lift coefficient $C_L = 0.4$ in a square tunnel of height three times the span, at a Mach number of 0.9. Shown in Figure (2) is the lift interference parameter, δ, along the axis of the tunnel for completely solid, completely slotted and partially slotted walls. In all cases, eight reflections around each wall of the horseshoe vortex representing the wing were used with strips extending over the range of x from -3 to 4 (all dimensions are scaled to the wing of unit span). The partially slotted tunnel considers slots extending from x = -2 to x = 2 with a slot parameter K = 0.5. These computations have been carried out in a quarter-plane. Several combinations of strips and panel lengths were used to indicate the sensitivity of the solution to the number of strips and panels. As indicated in the figure a rather small number of strips

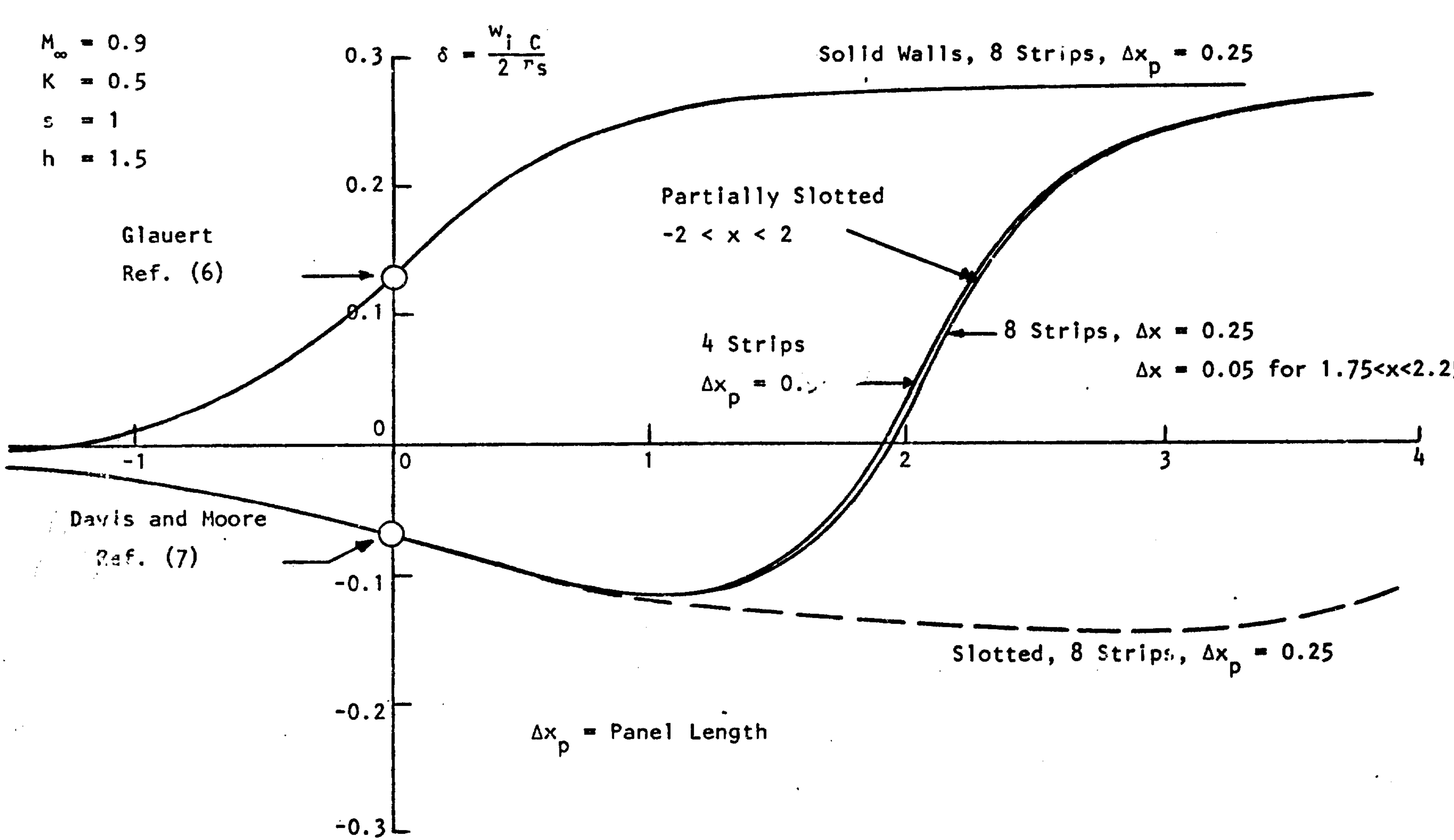

FIGURE 2. LIFT INTERFERENCE PARAMETER ALONG TUNNEL AXIS FOR SEVERAL WALL CONFIGURATIONS

and panels is sufficient to accurately predict wall interference along the tunnel axis. Also indicated in the figure are comparisons at $x = 0$ with other known solutions (References 6 and 7).

In the case of partially slotted walls, the drastic change in the interference pattern in the region near the downstream transition from slotted to solid wall was expected. What is of practical importance is the extent of this region in terms of wing span and of tunnel height. The effect of shortening the downstream extent of the slotted walls is shown in Figure (3) where results are presented in terms of the similarity variables $x/2\beta h$ and $\ell/2\beta h$. Not only can the effect of the transition from slotted to solid wall be felt at the wing location, if the wing is relatively close to the end of the slotted section, but more importantly, in the case of a model with a tail, the latter may experience a different wall interference than the wing. Thus, the pitching moment of the model may be directly affected by the finite length of the slotted test section.

Complimentary to the results of Figure (2) are those presented in Figures (4), (5) and (6). Shown in Figure (4) are axial distributions of the flow velocity (in terms of the parameter $wC/2\Gamma s$) through the slotted portion of the walls at two selected locations along the top and bottom walls. Similar distributions on the sidewalls are shown in Figure (5). Figure (6) shows the variation of lift interference for several values of the slot parameter K. The result reiterates, as is well known, the sensitivity of δ to values of K, (as well as to the parameters P and n when a more general boundary condition of the type $\Phi_x + K\Phi_{xz} + P(\Phi_z)^n = 0$ is used, c.f. References 3 and 8).

As indicated in some detail in Reference (8), mass flow into the plenum may alter plenum pressure conditions with respect to the usually assumed free stream static pressure value. Within the present formulation it is possible to examine the effects of a small perturbation in the plenum pressure. A computation has been performed by increasing the pressure in the bottom plenum to a constant value of $1.002\ p_\infty$ (pressures of this order were observed at certain plenum locations during the experiment reported in Reference 9), while retaining a value of $p = p_\infty$ along the other walls. Under these conditions, the boundary condition of Equation (1) can be rewritten, along the bottom wall, in the form

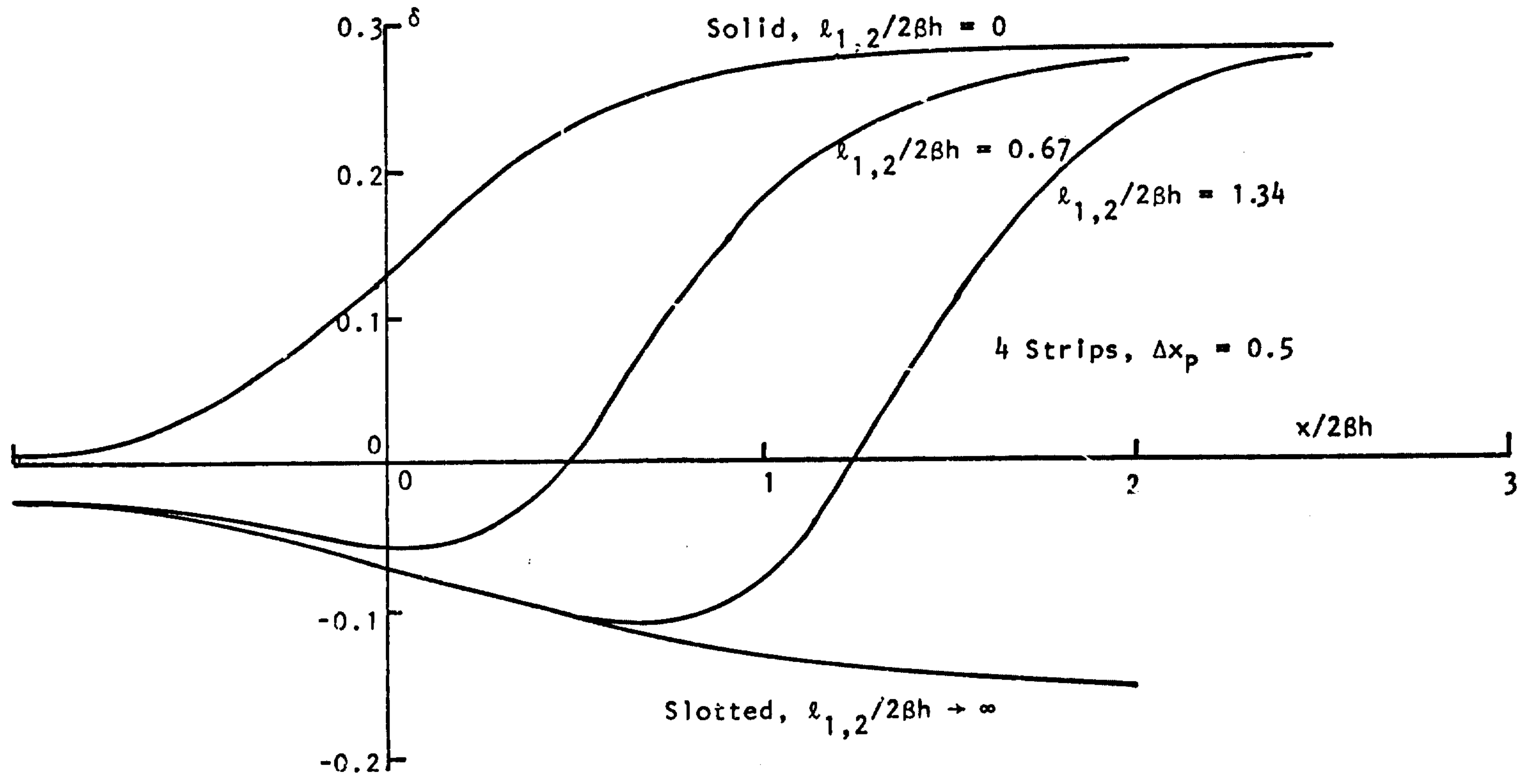

FIGURE 3. INTERFERENCE PARAMETER ALONG TUNNEL AXIS FOR SEVERAL LENGTHS OF SLOTTED SECTION

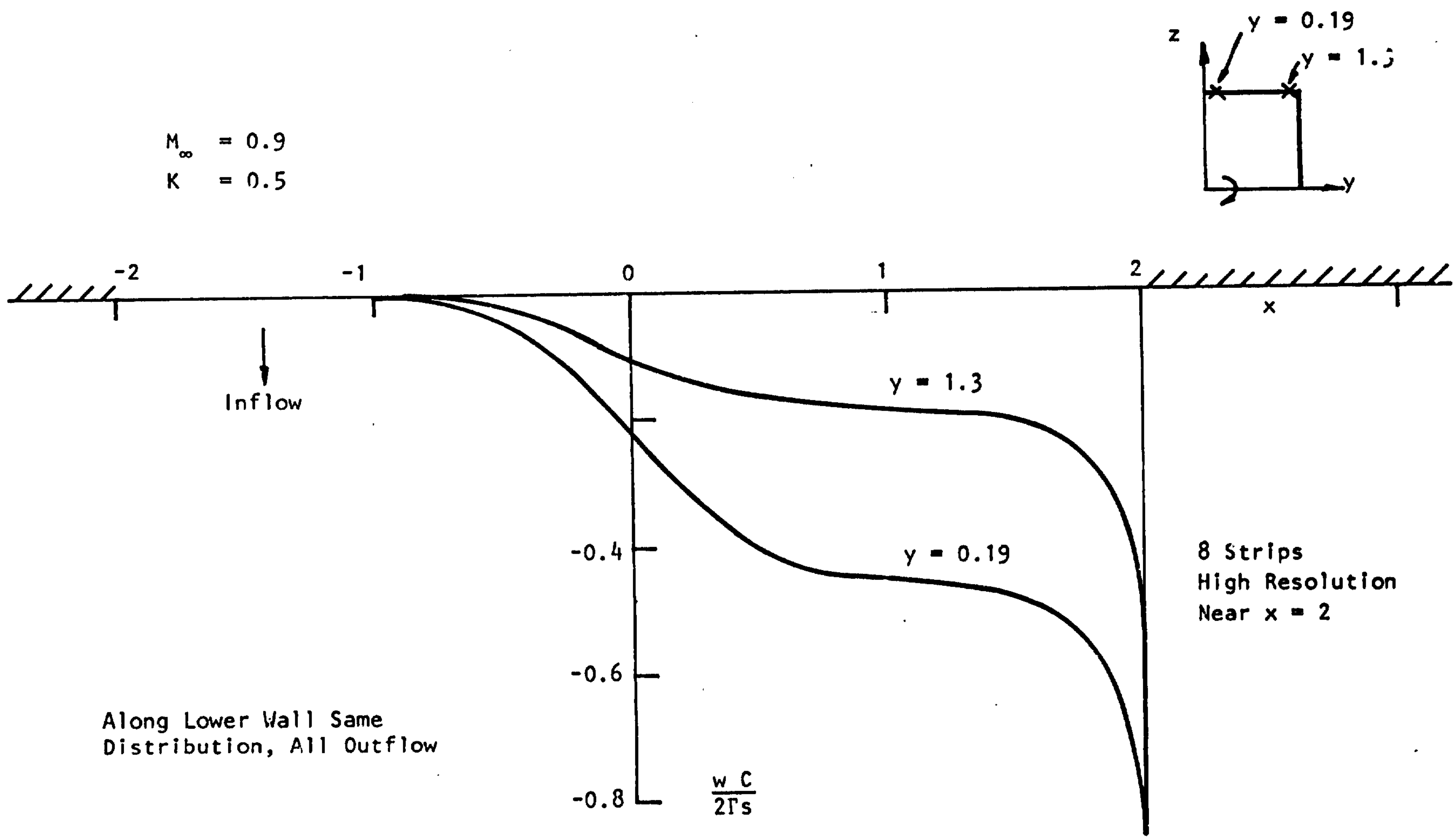

FIGURE 4. FLOW VELOCITY DISTRIBUTIONS ALONG UPPER AND LOWER WALLS

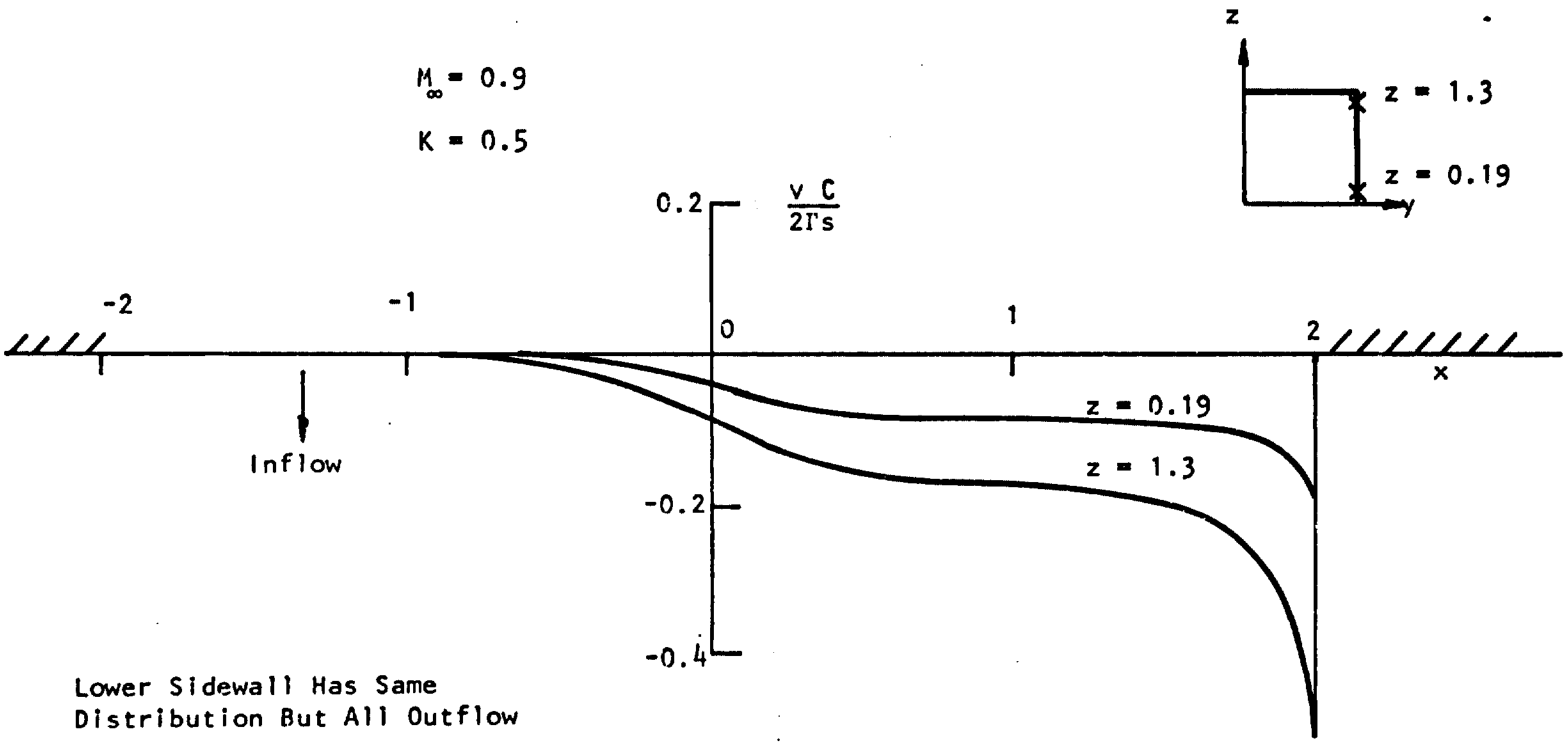

FIGURE 5. FLOW VELOCITY DISTRIBUTION ALONG SIDEWALLS

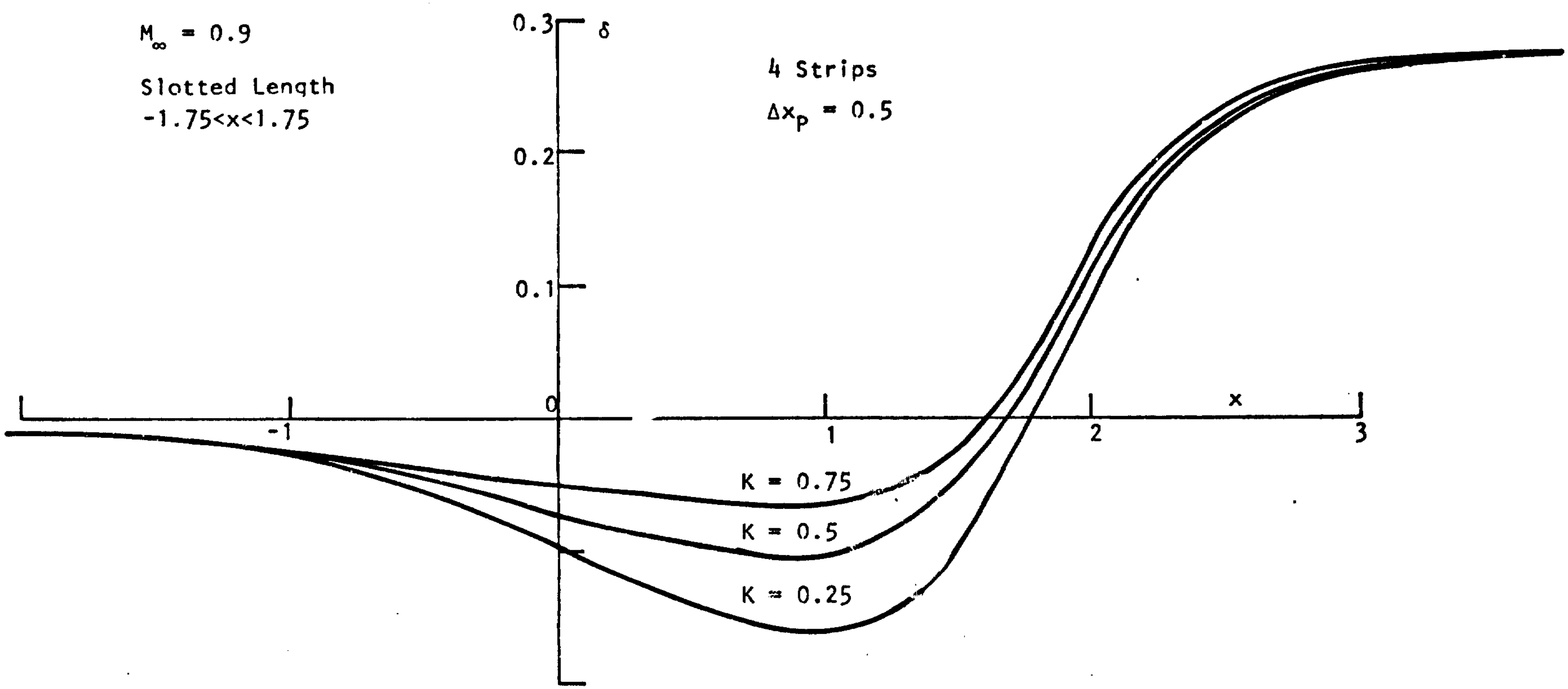

FIGURE 6. EFFECT OF SLOT PARAMETER ON LIFT INTERFERENCE

$$\Phi_x - K\,\Phi_{xy} = (1 - p_p/p_\infty)\gamma M_\infty^2$$

and the computational procedure carried out in the usual manner. The effects on lift interference of this increase in pressure are significant, as shown in Figure (7), where the comparison between this situation and the one where the plenum pressure is taken constant on all four sides is shown. At the same time, the outflow through the bottom wall is greatly reduced, as typically shown in Figure (8), whereas the upper wall inflow is only slightly reduced.

Inflow of stagnant air from the upper plenum into the tunnel will also cause an asymmetric development (with respect to tunnel centerline) of the viscous flow layer along the solid walls downstream of the slotted section. To investigate, at least in a qualitative manner, this effect and also to investigate the magnitude of a centerline axial pressure gradient which may be caused by a variation in cross sectional area downstream of the slots, two computations have been performed with modified solid walls and with the same lifting wing of unit span and $C_L = 0.4$ in the tunnel. In one case, the upper downstream solid wall was assumed to converge from $x = 1.75$ (end of the slots) to $x = 4$ by an amount of 0.05, a number consistent with expected boundary layer growth. In the other case, both upper and lower walls were taken as convergent. The sidewalls were left straight. Consistent with linear theory, the wall boundary conditions are changed such that the velocity perturbation normal to the wall is equal to the slope. The centerline pressure distribution $C_p = - 2u/U_\infty$ for the two cases (one wall or both upper and lower wall modified) are shown in Figure (9). It can be noticed that the pressure effect can be felt up to the region of the model and can be substantial. Shown in Figure (10) is the lift interference δ. When both walls are modified, the lift interference is the same (as it should be) as in the case of a straight wall, but when only the upper wall is modified the variation of δ may be significant near the end of the slotted region.

CONCLUDING REMARKS

The range of validity of the linear representation of the flow fields considered here is limited to Mach numbers below the transonic range. Nonlinear

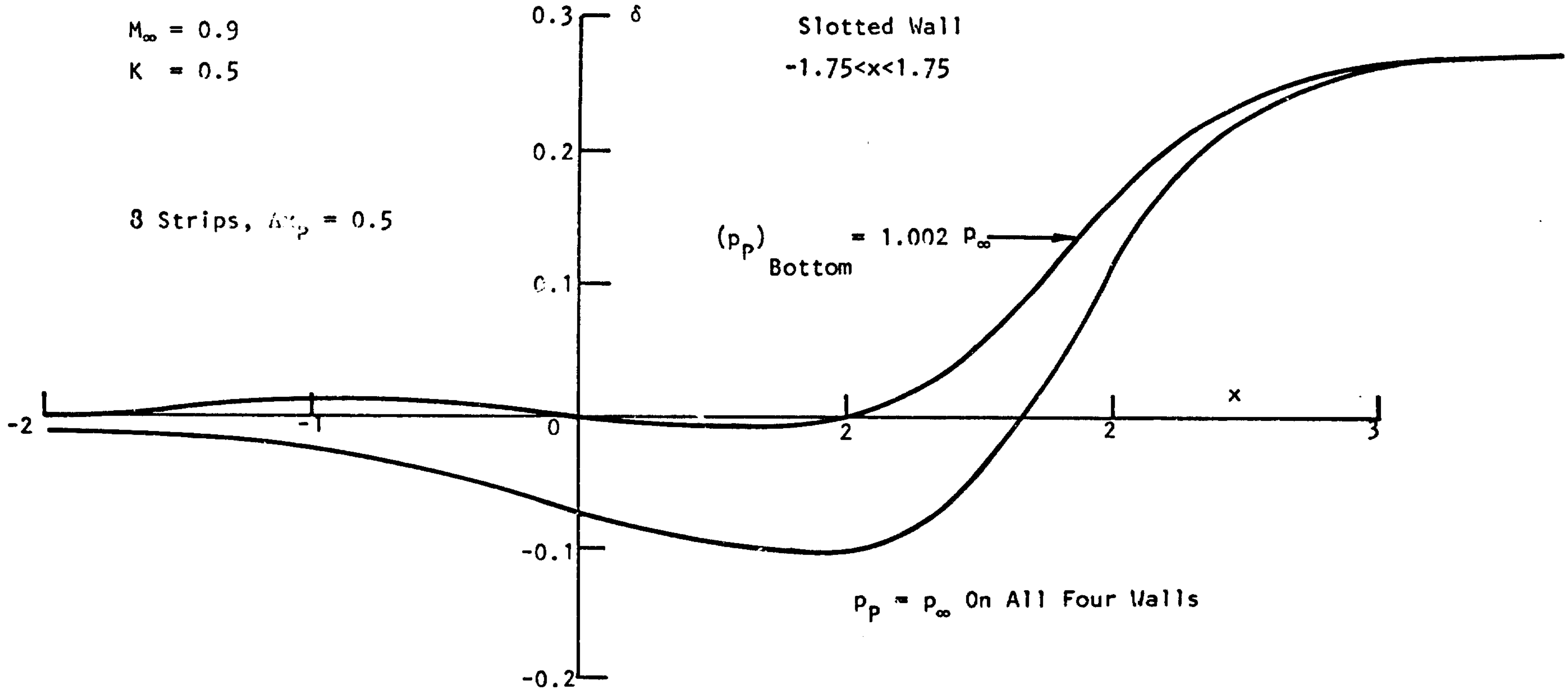

FIGURE 7. EFFECT OF AN INCREASE OF BOTTOM PLENUM PRESSURE ON INTERFERENCE PARAMETER

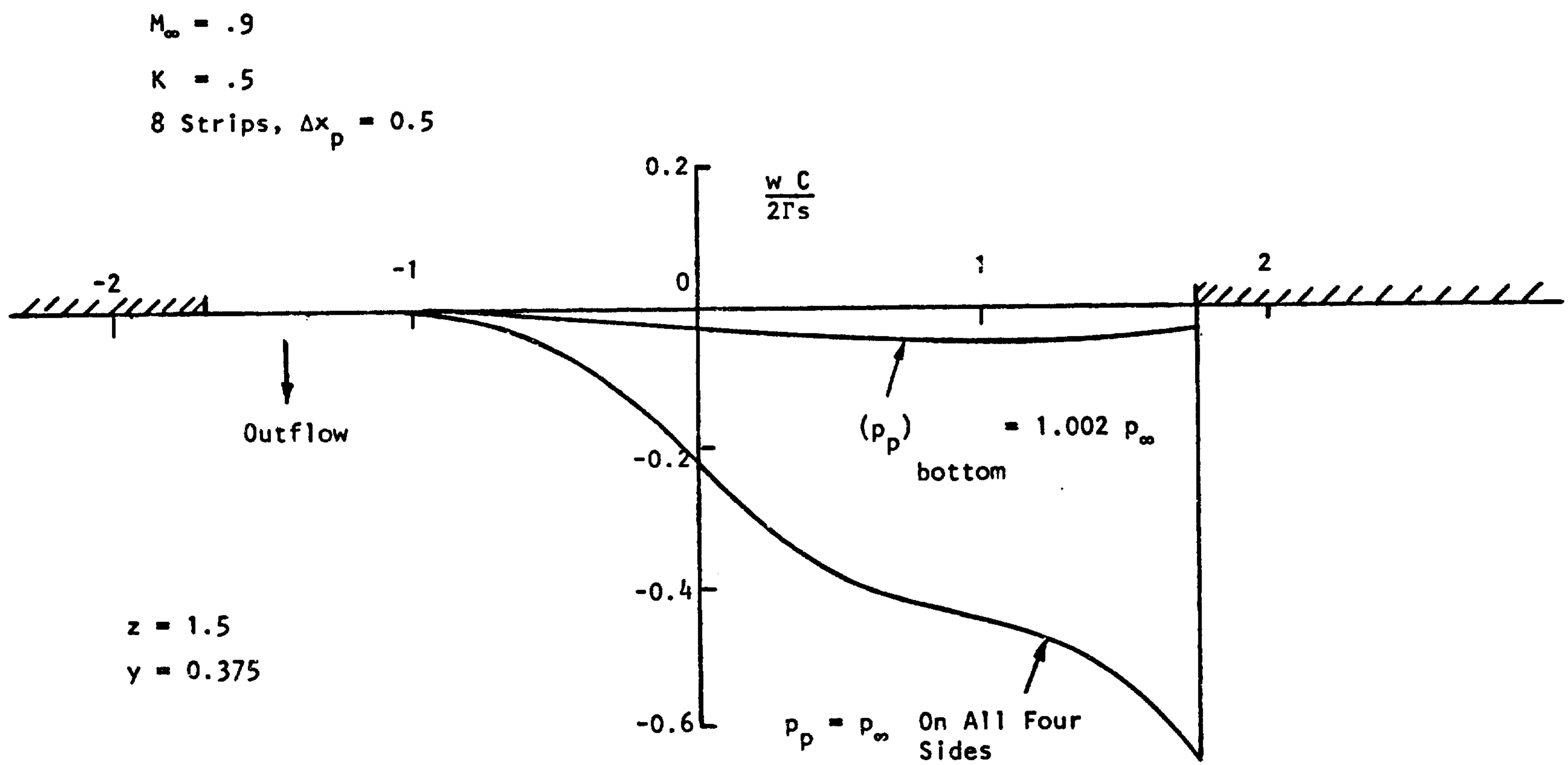

FIGURE 8. EFFECT OF INCREASE OF BOTTOM PRESSURE ON OUTFLOW FROM LOWER WALL

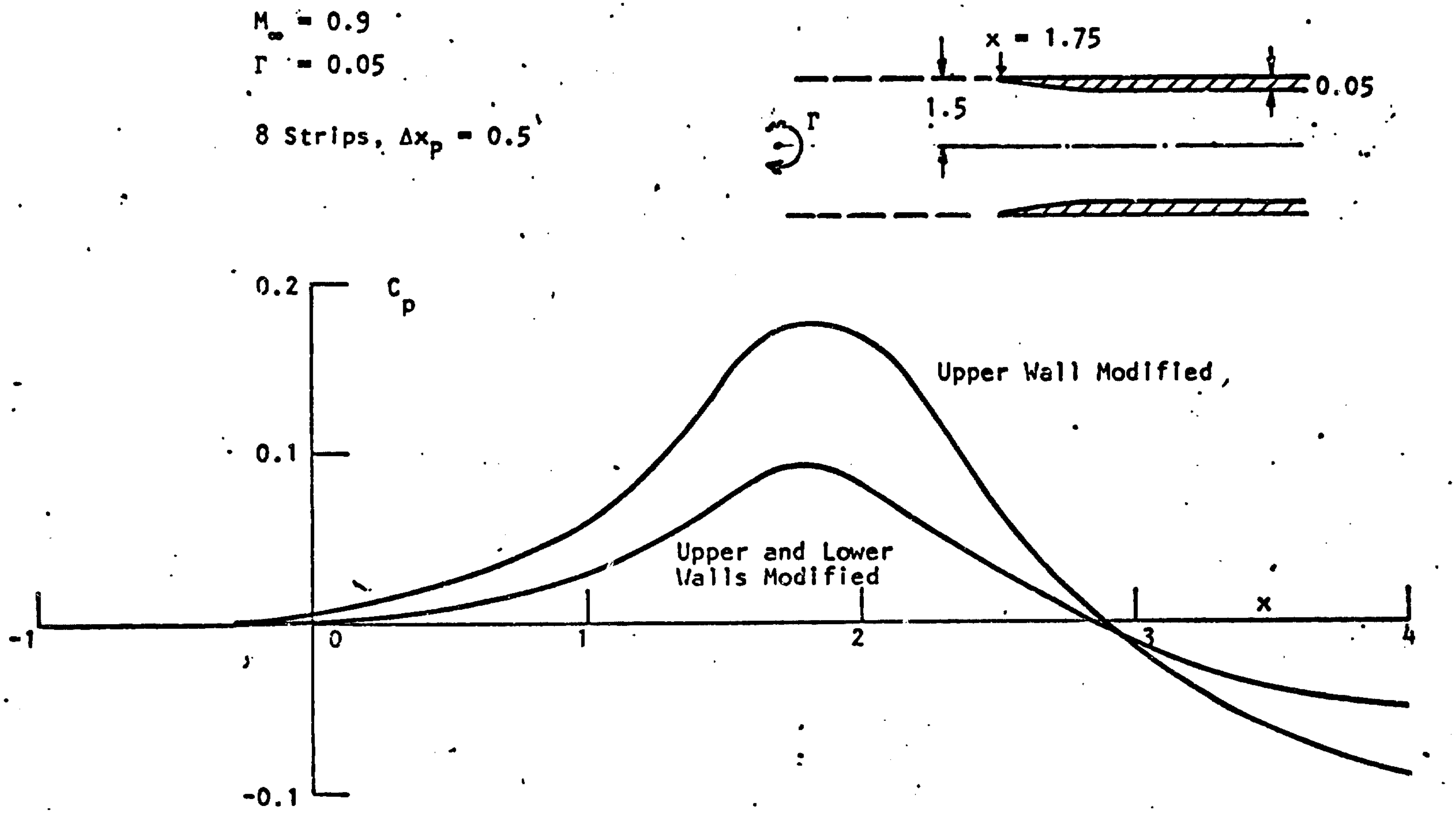

FIGURE 9. CENTERLINE PRESSURE DISTRIBUTION INDUCED BY MODIFICATION OF SOLID WALLS DOWNSTREAM OF SLOTS

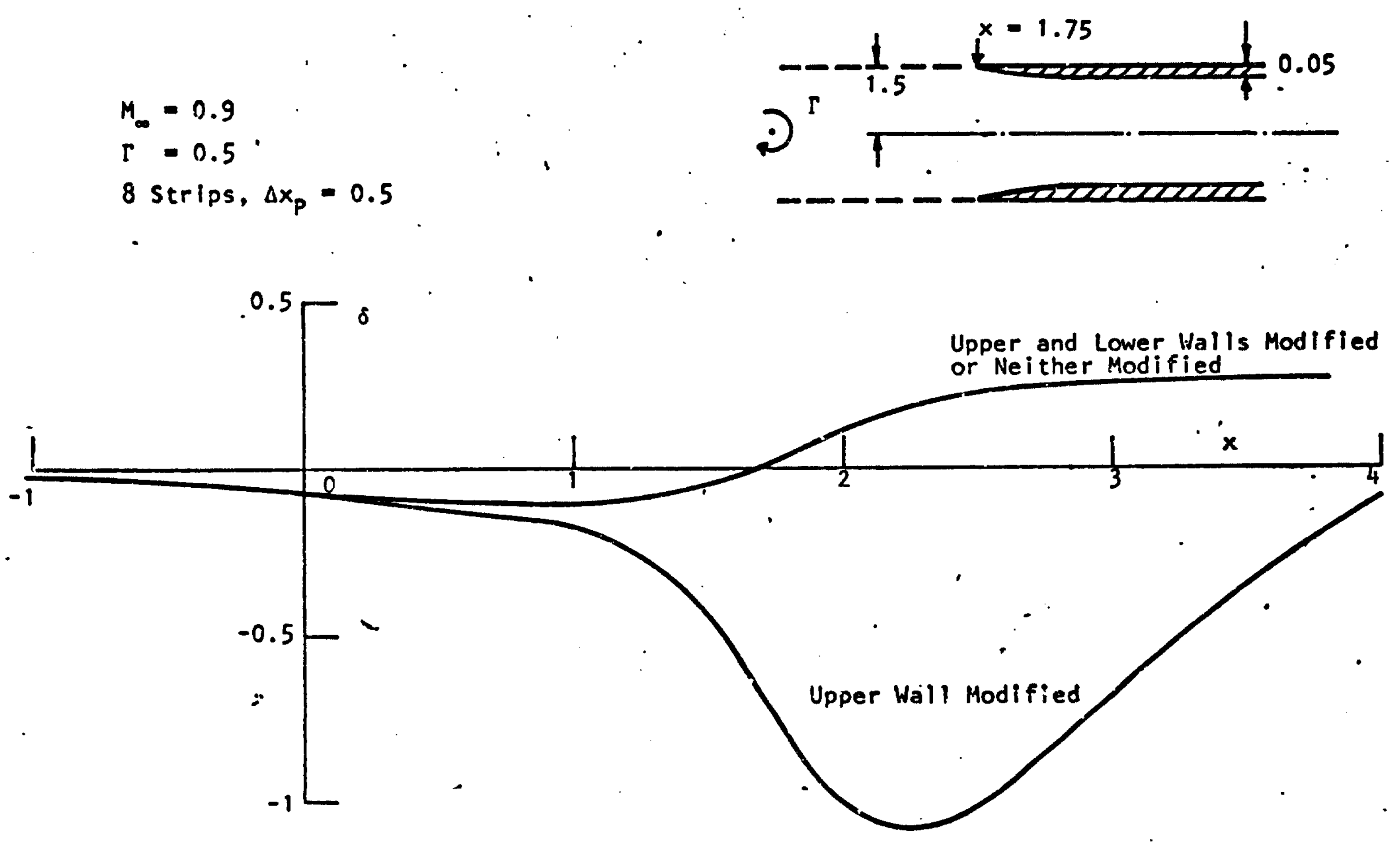

FIGURE 10. EFFECT OF MODIFICATION OF SOLID WALLS DOWNSTREAM OF SLOTS ON INTERFERENCE PARAMETER

effects are certainly of importance in transonic interference, c.f. also Reference (10); thus more refined numerical calculations with the nonlinear transonic equations may be warranted. The present analysis and results, although more of a qualitative than a quantitative nature are, however, indicative of important trends of interference patterns in tunnels with slotted test sections of finite length.

The finite length of the test section appears to be of importance for the definition of interference at the wing location and for the correct interpretation of pitching moment measurements of complete configurations, when the model is placed near the end of the test section, as is the case with some present installations. More significantly, the present results indicate the strong sensitivity of the lift interference to the properties of the slotted wall (a well known fact) and to small perturbations of flow conditions which could be present in the wind tunnel, such as variations of static pressure between lower and upper plenum. These variations can be generated by the loss of momentum of high velocity air entering the plenum, by pressure losses of air circulating from bottom to upper plenum and, at transonic speeds, by the different mass fluxes of air entering the tunnel (above the wing) and entering the plenum (below the wing), because of the different temperature of the two streams. Also, the admission of stagnant air from the plenum into the tunnel decreases the momentum of the tunnel flow and can produce a small pressure rise in the flow downstream of the slotted section. This can affect the lift interference and create axial pressure gradients.

It is evident that a quantitative definition of the perturbations induced in the tunnel flow by the slotted test section is needed for a firmer assessment of interference effects. These effects can be accounted for and possibly corrected, for a given tunnel configuration, if pressure measurements are taken during a test at or near the tunnel walls, both along slotted and solid sections. These measurements will define directly the wall boundary conditions thus bypassing the necessity of using the uncertain homogeneous boundary conditions. The present analysis, once further developed to include wing-body configurations, can permit the determination of interference effects and indicate the feasibility of first order corrections by simple modifications of wall characteristics (for instance, slightly convergent test section, and differential

variation of plenum pressure between upper and lower end of the slotted section) when the tunnel flow is subsonic.

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